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RESEARCH ARTICLE

Laser stripping of fiber Bragg grating polymer coating using pulsed 10.6 μm TEA CO_2 laser

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Abstract Stripping the polymer coating is the first step for the fabrication of fiber Bragg grating (FBG). The conventional stripping approaches are labor intensive and time consuming. Because of high precision and throughput, as well as non-contacting, laser stripping obtained more and more attention in recent years. This paper reports the primary experiments on laser stripping of polymer coating from FBG using pulsed transverse electric atmospheric (TEA) CO_2 laser with wavelength of 10.6 μm and pulse width of 2 μs. Using cylindrical lenses, the coating can be removed thoroughly at one time. The theoretical analysis and experimental investigations were carried out. The influence of laser fluence and pulse number on stripping quality has been investigated. Scanning electron microscopy (SEM), optical microscope, and electrical balance were employed to detect the quality removal. The result shows that excellent quality removal is possible by using pulsed 10.6 μm TEA CO_2 laser.

Keywords laser stripping, fiber Bragg grating (FBG), TEA CO_2 laser

1 Introduction

Since fiber Bragg grating (FBG) is found in more and more industrial applications, such as utilized in fiber laser, fiber amplifier, fiber filter, high-speed telecommunications, monitoring the structural health of buildings, bridges, or vehicles, as well as providing means of data communication within these structures, the research of fabrication of FBG with low cost and high throughout is attractive [1,2]. Generally, four steps are needed to fabricate FBG, including stripping of polymer coating, writing of grating in the fiber, annealing of the grating, and recoating of the stripped region of the fiber. The object of stripping polymer coating before the writing of the grating is to allow the ultraviolet (UV) or infrared (IR) laser to reach the glass cladding without suffering absorption loss [3]. The conventional approaches to remove the polymer coating are manual, mechanical, and chemical. However, these traditional stripping processes are labor intensive and time consuming. For example, the manual stripping process is time consuming and labor intensive, mechanical process may cause the possible structural damage, and the chemical method brings environmentally undesirable chemicals. Advanced techniques for the localized removal of FBG's outer coating are necessary.

Laser stripping has obtained an increasing attraction in recent years. Comparing with the conventional means, laser stripping offers precision and speed without the necessity of contacting the material. Ogura could cleanly strip acrylate and polyimide coatings from either single or ribbon fibers using ultraviolet laser [4]. Obata et al. [5] and Zhou et al. [6] also investigated the stripping using excimer laser and YAG laser, respectively. Barnier et al. [7] have investigated the influence of the laser's wavelength on the removal of the fiber's polymer jacket, and it was found that excimer lasers with 248 and 193 nm could remove the polymer coating very well without any damage. The CO_2 laser with wavelength of 9.2 and 9.6 μm [3] also brought good quality. However, in this process, the fiber was irradiated at least 400 pulses for a thorough stripping of fiber coating. In Ref. [3], a 9.6 μm laser light was split into two arms and was directed at a static fiber from opposite directions. Both beams were scanned in synchronism along the fiber to strip a predefined length of coating in a sealed environment filled with H_2 gas, and this method improved the throughout of the recoating. However, the output of the wavelength of 9.2 and 9.6 μm are much lower than that of 10.6 μm for CO_2 lasers. Furthermore, the 10.6 μm CO_2 lasers are more common as industrial tools. Therefore,

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stripping the FBG's outer coating using 10.6 μm CO_2 laser was active in the past several years, although the results were not satisfactory. Brannon et al. [8] attempted to strip the polyurethane coat from the wires. In this process, 300 pulses at 5 J/cm^2 for each 90° rotation were used. However, incomplete removal and badly roughened surface were found after the process. Tarpey et al. used 10.57 and 10.63 μm continuous CO_2 to strip the polyimide fiber but also failed. They found that many fibers were not properly stripped instead of charred, and some of fibers were even seen with occasional "pinholes" in the glass [9]. However, the above used 10.6 μm CO_2 lasers were operated in continuous wave mode (CW) or long pulse duration, resulting in low peak power, which brought high thermal stresses in fibers. The pulsed 10.6 μm transverse electric atmospheric (TEA) CO_2 laser has the narrow pulse duration and high peak power. Using this laser as a tool to strip, the FBG's coating has not been reported until now. This paper studied on the feasibility of the laser stripping FBGs by using 10.6 μm TEA CO_2 pulse laser and investigated the influence of the process parameters on stripping qualities.

2 Theoretical analysis

2.1 Stripping regime

For the laser stripping of fiber, different regimes may occur: thermo decomposition, vaporization, melt and blowing, and cold stripping, depending on the laser wavelength, pulse energy, and materials performance, i.e., fragment bond energy. In general, if energy of the laser photon E_P is larger than the fragment bond energy E_0, i.e.,

$$E_P > E_0, \tag{1}$$

the stripping mechanism is photochemical, and the removal of the coating relied on cold stripping. The photon energy E_P of laser is decided as [10]

$$E_P = h\nu = \frac{hc}{\lambda}, \tag{2}$$

where h is Planck's constant (6.625×10^{-34} J.S), ν is the frequency, λ is the wavelength of laser, and c is the velocity of light (2.99×10^8 m/s). Table 1 shows the general fragment bond energies of the macromolecule and their corresponding wavelength.

For the fiber, the polymer coating is acrylate, which includes fragments of C–C, C–O, and C–H. If the fiber is irradiated by the laser with a wavelength shorter than 342 nm, the fragment bonding can be broken by a regime named of thermal chemical. However, the wavelength of CO_2 laser is only 10.6 μm, in which the photo energy is much lower than the bond energies of the fragment of fiber coating. Therefore, bond-breaking cannot take place, instead of thermo decomposition, vaporization, or melt and blowing, depending on the laser fluence. During the process, the fiber surface absorbs the laser energy, which induces the local temperature rise. If the absorbed energy is sufficiently high, inducing temperature rise exceeds the vaporization point or thermo decomposition point, evaporation occurs, leading to the local material being removed. If the power density is not high enough, only the surface of the fiber is melted, i.e., the focused beam first heats up the surface to the melting point, helping by the blowing, the stripping also can happen. If the power density is too low, the surface of the fiber cannot melt, and the stripping cannot happen.

2.2 Stripping depth

The rate of penetration of the beam into the work-piece can be estimated from a lumped heat capacity calculation, assuming the heat flow is one dimensional, and all of it is used in the vaporization process, that is, that the heat conduction is zero. Since the thermal conductivity of fiber is very small, the little absorbed laser energy is lost by conduction. Thus, the depth Δd removed per pulse can be calculated as

$$\Delta d = \frac{AE}{2\rho[H + C_p(T - T_0)]L\pi R}, \tag{3}$$

where A is the light absorbance, ρ is the density of the fiber coating, H is latent heat of fusion and vaporization, C_p is heat capacity, T is the vaporization temperature, T_0 is the temperature at start, L is the length of the coating needed to remove, R is the radius of the fiber, and E is laser pulse energy. From Eq. (3), it can be found that the depth removed per pulse increases with the increase of the single pulse energy. For the definite depth coating d, the single pulse energy needed for stripping the fiber can be simply related as follows:

$$E = \frac{2\pi LRd[H + C_p(T - T_0)]}{AN}, \tag{4}$$

where N is the pulse number. From Eq. (4), it can be seen that for the predefined length fiber coating, the recoating can be achieved by combining different single pulse energy and pulse number; the pulse number needed decreases as the single pulse energy increases.

Table 1 Fragment bond energies and their corresponding wavelength

bond	C=O	O=O	C–F	O–H	C–H	C–O	N–H	C–C	C–Cl	C–N
bond energy/(kcal·mol^{-1})	192	119	119	110.6	98.8	87	84	83	78.5	68
wavelength/nm	148	240	240	260	290	330	340	342	364	420

2.3 Thermal diffusive depth and thermal stress

The thermal diffusive depth δ [11] and approximately thermal mechanical stresses F are all proportional to the pulse duration τ [12]:

$$\delta = \sqrt{\kappa\tau}, \tag{5}$$

$$F \propto \sqrt{\tau}, \tag{6}$$

where τ is the pluse duration, κ is thermal diffusivity, for the acrylate. From Eqs. (5) and (6), it can be found that the thermal diffusion depth and the thermal stresses caused by laser irradiation decrease with the decrease of the pulse duration. Thus, short pulse duration is beneficial for stripping the fiber coating. This may be the reason that the previous researches using CW CO_2 laser or long pulse duration showed unexpected results. However, for the TEA CO_2 laser, the pulse duration is only 1–2 μs. Therefore, the thermal diffusive depth and thermal stress are much smaller than that of using CW or long pulse duration CO_2 laser, which may reduce the possibility of producing "pinholes" or cracks in the fiber core significantly.

3 Experiments

The experiments were carried out on a self-developed TEA CO_2 laser with a wavelength of 10.6 μm, maximum single pulse energy of 3 J, and frequency of 2 Hz. The laser produces an initial gain-switched spike of approximately 64 ns full width at half-maximum (FWHM) in duration, followed by a 2 μs tail, as shown in Fig. 1. The pulse energy is roughly equally split between the spike and tail regions. I_0 in Fig. 1 is the laser power density.

Before reaching to the fiber, a mask splits the laser into two parallel beams. Both beams were then guided to two reflectors and reached a cylinder mirror, respectively. The cylinder mirror focused the laser to be approximately 20 mm×0.5 mm and was directed at a static fiber from opposite directions at the same time. The setup is shown in Fig. 2. The laser was carried out at a repetition rate of 1 Hz, single energy range of 1.5–3 J/pulse. Each laser beam that reached the fiber was at the energy range of 0.5–1.0 J/pulse.

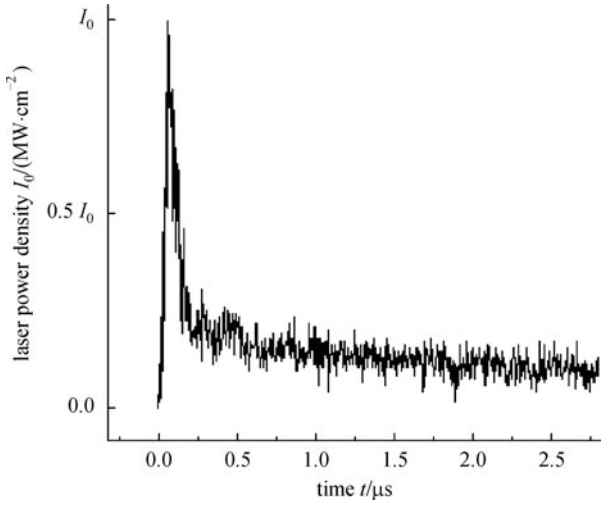


Fig. 1 Pulse shape of TEA laser

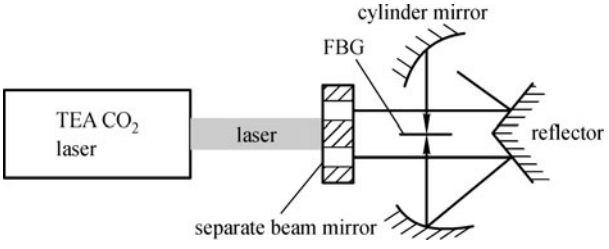


Fig. 2 Schematic set-up for laser stripping FBG

The fiber used in this experiment was a common photosensitive fiber composed of three layers: core with 9 μm diameter, cladding layer with 110 μm diameter, and coating layer made from acrylate with a 245 μm diameter. The fiber was used in the experiment without any handling except cutting into 60 mm length.

The pulse energy and shape were measured by laser power meter and photo-drag detector, respectively. Scanning electron microscopy (SEM) (Quanta 200, Sirion 200) and microscopes were used to characterize the surface morphology of the fiber. The lost weight was measured by an electrical balance. Each experiment was repeated ten times. All the data was the average value of ten readings.

4 Experimental results and discussion

The influence of laser fluence and pulse number on lost weight of the fiber caused by laser irradiating is shown in Fig. 3. In Fig. 3, it can be found that if the pulse energy keeps constant, the amount of fiber weight lost increases with the pulse number; this experimental result verifies the

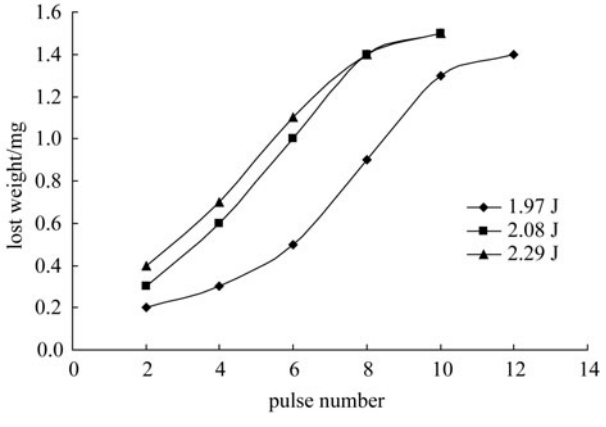


Fig. 3 Pulse number and pulse energy dependence of lost weight

above theoretical analysis. However, the dependence on pulse number is weak for the high pulse number. For the low pulse number, the lost weight is proportional to the pulse number. If the pulse number is large, the increment of the lost weight decreases. As the pulse number increases continuingly, the fiber almost keeps constant weight, indicating the thorough recoating. The larger the pulse energy, the more evident the phenomenon shows. For instance, when the pulse energy was kept at 2.29 J, the lost weight of the fiber increases with the increase of the pulse number until the pulse number achieves 8. When laser irradiated eight pulses to the fiber, the fiber lost 1.4 mg weight, 0.175 mg per pulse. Continuously irradiated by the laser to 10 pulses, the lost weight of the fiber is only 1.5 mg, i.e., 0.1 mg increment only, and 0.05 mg per pulse for the last two pulses, which is much lower than the average lost weight of the previous eight pulses. For the different pulse energy, the fiber lost same weight can be achieved by using different pulse number. The higher the pulse energy, the lower the pulse number needed. However, these lost weights seem to have an upper limit. For the pulse energy of 1.97 J, lost 1.4 mg weight needs 12 pulses, but for the pulse energy of 2.08 and 2.29, lost 1.4 mg weight only needs 8 pulses, suggesting the higher throughput.

In Fig. 3, it also can be found that when keeping the pulse number constant, the lost weight increases with the increasing pulse energy. However, if the fiber is irradiated by enough laser pulse number, the lost weights of the fiber for the different laser energies are same. For example, for the pulse energy of 2.29 J and pulse energy of 2.08 J, if eight laser shots irradiated the fiber surface, the lost weights are almost same. This is because that the fiber coating is stripped thoroughly.

Several typical surface morphologies of the fiber after laser stripping are shown in Figs. 4–7. The polymer coating of the fiber in Fig. 4 is not removed completely. The process parameters used in this experiment were the fluence of 6.65 J/cm^2 and pulse number of 10. Remaining polymer can be found from this figure. The higher magnification view of Fig. 4 is shown in Fig. 5, it can be clearly found that the thickness of polymer coating is much less than the coating, suggesting that the polymer is removed layer by layer.

The sample in Figs. 6 and 7 was stripped by using fluence of 7 J/cm^2 and pulse number of 10. From these two figures, it can be seen that the polymer coating were removed perfectly, and no cracks and debris as well as "pinholes" can be found on the surface of the fiber,

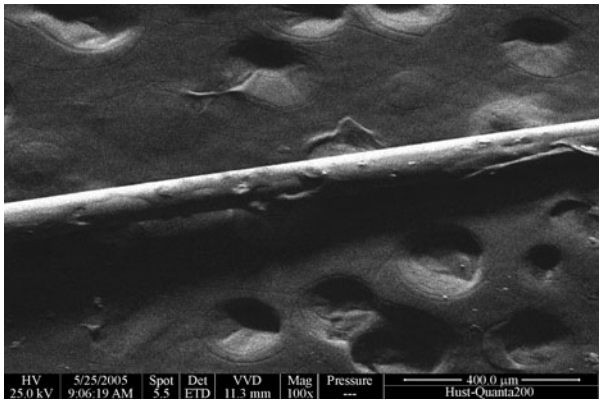


Fig. 4 SEM photo shows incomplete recoating of laser stripping

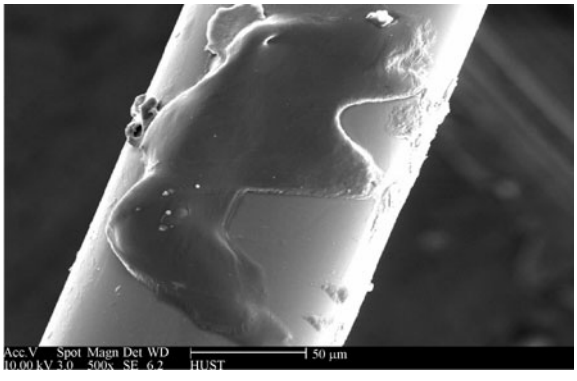


Fig. 5 Magnification of Fig. 4

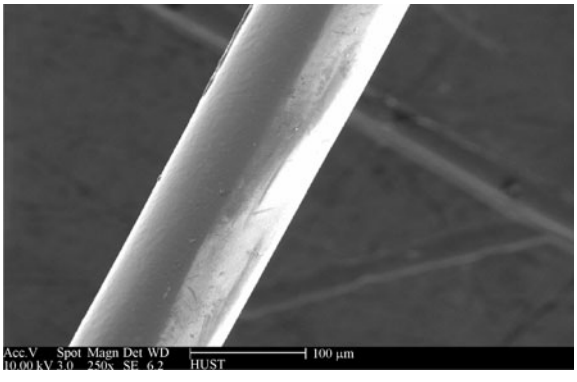


Fig. 6 SEM photo shows complete recoating of laser stripping

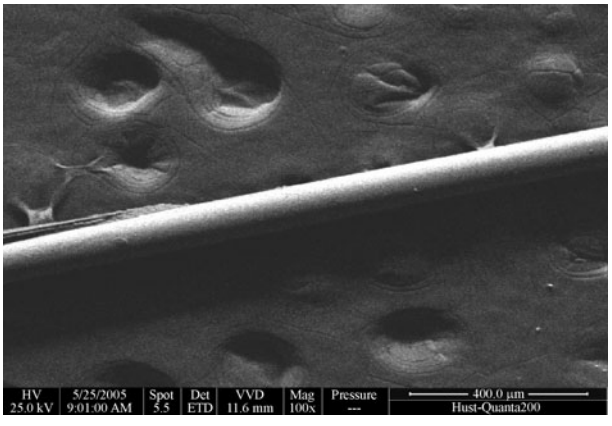


Fig. 7 SEM photo of interface region of laser stripping fiber

suggesting that excellent quality for stripping the fiber is possible by using TEA CO_2 pulse laser with wavelength of 10.6 μm. It can also be found that the interface region is ragged and poorly defined, indicating that the further optimum of optical configuration is necessary.

5 Conclusions

Process parameters have a significant effect on the stripping quality. If the pulse energy keeps constant, the amount of fiber weight lost increases with the pulse number. However, the dependence on pulse number is weak for the high pulse number. If the pulse number is kept constant, the lost weight increases with the increasing of the pulse energy. TEA CO_2 pulse laser with wavelength 10.6 m can meet the requirements of stripping the fiber coating very well. By using different laser fluence and pulse number, optimal process parameters can be obtained. However, increasing pulse energy may improve the throughput.

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